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Microcontroller-based Inverter for 500W Residential Wind Generator

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***Abstract*—**In this project, an inverter circuit with suitable control scheme design was developed using Microcontroller PIC16F887. The circuit was to be used with a selected topology of Wind Energy Conversion System (WECS) to convert electricity generated by a 500W direct-drive permanent magnet type wind generator which is typical for residential use. From single phase AC output of the generator, a rectifier circuit is designed to convert AC to DC voltage. Then a DC-DC boost converter is used to step up the voltage to a nominal DC voltage suitable for domestic use. The proposed inverter then will convert the DC voltage to sinusoidal AC. The duty cycle of sinusoidal Pulse-Width Modulated (SPWM) signal controlling switches in the inverter was generated by a microcontroller. The lab-scale experimental rig involves simulation of wind generator by running a geared DC motor coupled with 500W wind generator where the prototype circuit was connected at the generator output. The experimental circuit produced single phase 240V sinusoidal AC voltage with frequency of 50Hz. Measured total harmonics distortion (THD) of the voltage across load was 4.0% which is within the limit of 5% as recommended by IEEE Standard 519-1992.

***Keywords*—** Microcontroller, wind energy, inverter, converter, generator, residential electricity.

I. INTRODUCTION

WIND energy is the world's fastest growing renewable energy source. The average annual growth rate of wind turbine installation is around 30% during last 10 years [16][17][25][30]. It is clear that the global market for the electrical power produced by wind turbine generators has been increasing steadily, which directly pushes the wind technology into a more competitive area.

Wind turbine is the device that converts wind energy into electricity [2][3]. The system is also generally known as Wind Energy Conversion System (WECS). Generally there are two types of wind turbine: horizontal-axis wind turbine (HAWT) and vertical-axis wind turbine (VAWT). The design of horizontal-axis wind turbine (HAWT) as shown in **Figure 1**, consisted of three components namely: 1) rotor component including blades for converting directional wind speed to rotational speed which constitutes 20% of cost, 2) generator component which is approximately 34% of cost, including electrical generator, gearbox (some design uses direct drive), and the control electronics, and finally 3) structural support component which is approximately 15% of the cost including the tower and rotor yaw mechanism [25]. Several types of generator were used in wind turbine particularly the HAWT types and the common ones were Permanent Magnet Synchronous Generator (PMSG), Doubly Fed Induction Generator (DFIG), Induction Generator (IG) and Synchronous Generator (SG) [2][8].

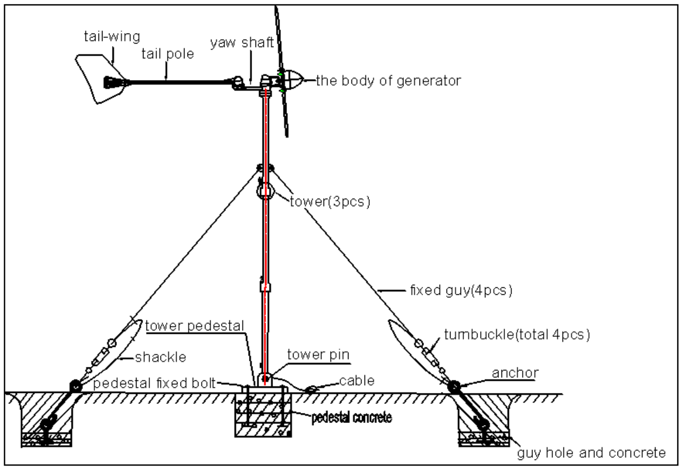

Figure 1 Installation diagram for HAWT [5]

Small wind turbines of generally less than 3kW are suitable to be residential type. Small types normally were installed at house lawn area such as the one shown in **Figure 1** and some were even small enough to be mounted on the rooftops. The type of generator favored for this segment was Permanent Magnet Synchronous Generator over other types since most urban areas in Indonesia have wind supply of less than 5m/s. Within these speeds, voltage generated at a particular 500W wind generator permanent magnet type is around 18V to 22V (fabricated by Anhui Hummer in 2007). A power converter system will then convert the generated electricity to the standard level for user consumption. If a small wind energy system of 500W can operate for 8 hours minimum, the particular household can save about 40% from the usual electricity bills. Lately, there is an increasing trend to enable the WECS to supply excess generated energy back to the electricity grid. The public demand for this capability is high on residential type market segment particularly after introduction of net-metering policy in some countries like United States and

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Canada, where consumers were allowed to sell back to the utility companies to offset their consumption [3].

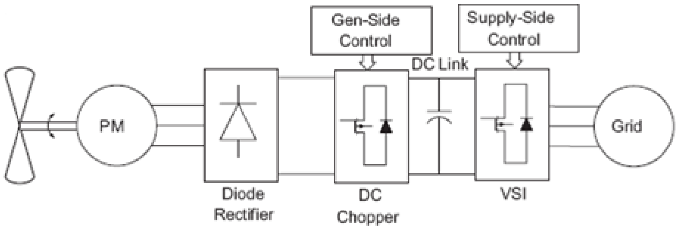

Figure 2 Wind energy conversion system (WECS) with diode rectifier converter options [9]

Inverter is actually another type of SMPS (Switched-mode power supply) device that transforms voltage from direct current (DC) to alternating current (AC) using switch topology. As shown in **Figure 2**, it is used together with a boost DC-DC converter and a rectifier circuit in power converter topology to increase the low AC voltage generated at wind generator terminal to nominal AC load and grid voltage. For a typical full bridge, single phase, voltage source inverter (VSI), the circuit consists of H-Bridge circuit containing power switches and inverter control circuit that generates triggering signal to switch the power switches in the H-Bridge circuit [1].

The objective of this research is to use Microcontroller PIC16F887 to develop and implement inverter control circuit for residential type wind generator with the capacity of 500W.

II. INVERTER SYSTEM

A. Control circuit

The project was expected to turn output voltage generated by a residential wind generator at 18V to 22V to household and consequently being grid compatible of single phase sinusoidal AC voltage of 240V ±5% with frequency of 50Hz. The total harmonics distortion (THD) of final output voltage must not exceed 5% as stated in the requirement. The proposed design should be able to meet the above requirements with much lesser components and lower cost.

This research was based on experimental approach. From the past research, selected relevant topology and basic circuit, the control algorithm was designed and model simulated under software MATLAB SIMULINK. As the simulation results confirm with the theoretical model, the values of circuit component were selected and the programming was verified. Then, the circuit was built on the prototype board. The circuit was designed under EAGLE software and built on prototype printed circuit board (PCB). Experimental data and result were collected from selected test points on the prototype board using oscilloscopes. The wind generator operation was simulated through a design rig. In the rig, the wind generator was rotated by a DC motor at various speeds from 118 rpm to 400 rpm to simulate its respond to different wind speed.

Microcontroller used in the system, particularly in the trigger circuit for Inverter Control is of model PIC16F877A. It is a 40-pin enhanced flash-type microcontroller produced by Microchip. This microcontroller was used to generate reference sine wave, carrier sawtooth wave, and also the two pulse control signals which were out of phase from each other. Some of the key features of the microcontroller, which were useful for the project, among others are 2 internal comparators, 5 Input/Output ports, 8 channel 10-bit analog to digital converter [23].

Inverter circuit main job function is to invert the stepped up voltage of 240V from DC to AC. The output voltage must be ideal sine wave with frequency at 50Hz and low total harmonic distortion. The circuit consists of H-bridge circuit and control trigger circuit. **Figure 3** shows the H-bridge prototype circuit schematic diagram. The H-bridge circuit consists of four MOSFET transistors Q2, Q3, Q4 and Q5 arranged in H-bridge formation. The input to the H-bridge circuit is the stepped-up DC voltage while the bridge output of the circuit is taken across points between source of Q2 and drain of Q4 and between source of Q3 and drain of Q5.

TABLE I shows components list that were used in the H-bridge inverter circuit.

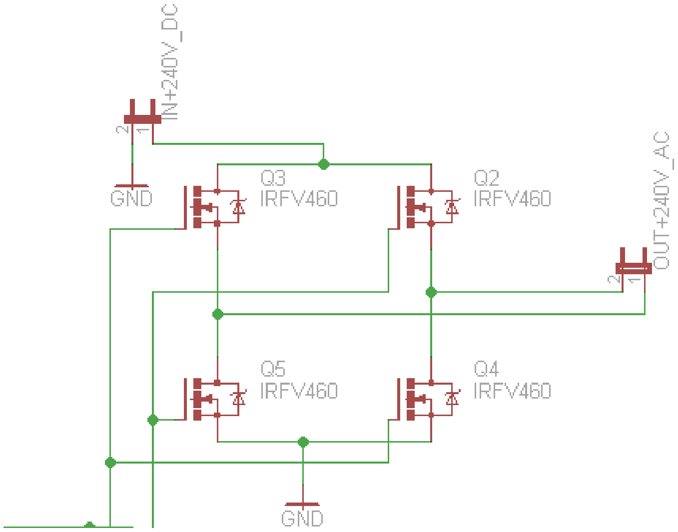

Figure 3 Schematic diagram of H-Bridge inverter circuit (shown without LC-filter components and load)

TABLE I COMPONENT LIST FOR H-BRIDGE INVERTER CIRCUIT

No	Components	Specifications	Quantity
1	MOSFET Q2, Q3, Q4, Q5	IRFP460/ 500V/20A	4
2	Inductor	18mH/ 3A	1
3	Capacitor	330uF/ 500V	1
4	Resistive load	480Ω/ 600W	1

B. *Control algorithm*

The input DC voltage will be fed through h-bridge circuit where the switches will be N-type MOSFET transistors IRFP460N. The switching of the MOSFET transistors must be out of phase for each diagonal pairs in order to generate square wave-like signal output. Also, the switching signal at the transistor gate must be high frequency chopped sinusoidal modulated pulse. To do that, trigger signal must be supplied to the H-bridge circuit gates in two channels. Channel 1 of the trigger signal will trigger MOSFET transistors Q3 and Q4 while Channel 2 of the trigger signal will trigger MOSFET transistors Q2 and Q5.

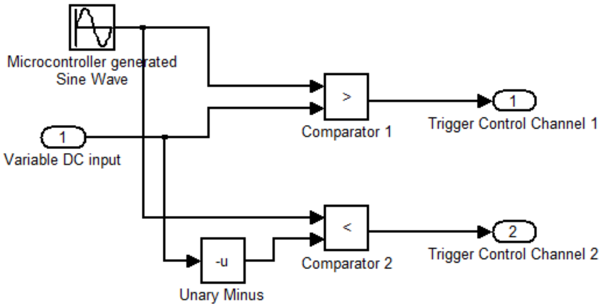

Figure 4 Block diagram for inverter trigger control

Figure 4 shows the block diagram for inverter trigger control design. The sine wave that is internally generated by the microcontroller is split to two channels. The sine wave must be non-biased. A variable DC signal is also split to two channels where one channel is negative biased of the other with similar amplitude. In comparator 1, the sine wave is compared with the positive DC input to generate trigger control Channel 1. In comparator 2 the sine wave is compared with the negative biased DC input to generate trigger control Channel 2. Amplitude of the DC input signal will determine width of the generated trigger control pulse. Smaller amplitude will increase the trigger control pulse width while bigger amplitude will decrease the trigger control pulse width.

After successful simulation of the control algorithm using MATLAB SIMULINK, hardware version of trigger control circuit is built and the algorithm was translated into C program that will be used by microcontroller. The trigger circuit mainly consisted of microcontroller PIC16F877A, comparator IC LM324, IC 74244. The microcontroller generates reference sine wave, carrier sawtooth wave, and also the two pulse control signals which were out of phase from each other. Through firmware, the reference sine wave signal was generated at Port B with frequency of 50Hz. Sawtooth carrier signal was generated at frequency 2kHz through initialization of PWM Module at pin CCP1, where the pulse signal was later modified to be sawtooth by filtering. Internal comparator modules C1 and C2 were activated through microcontroller firmware.

Figure 5 shows the block diagram of the flow of the experiment according to the selected topology. To simulate the problem statement, residential type wind turbine was to be used with condition of low wind power, with wind speed around 3m/s to 5m/s. Based from topology selected, the residential wind generator to be used is permanent magnet synchronous generator (PMSG), direct drive type (which does not utilize gear transmission to increase the turbine rotational speed). For this purpose, a 500W wind turbine system was purchased. Voltage generated at the generator terminal is single phase AC type and very low amplitude. The output voltage is then connected to rectifier circuit to transform the voltage to DC type. Next, boost converter was used to step up the voltage to nominal grid voltage of around 240V. After that, inverter circuit was used to invert the DC voltage to AC voltage. Necessary performance parameters of the output voltage such as amplitude, frequency and total harmonics distortion (THD) were measured and analyzed to ensure the generated output being compatible to be supplied to the grid. Voltage data from wind generator performance datasheet was used as basis during simulation stage where circuit at each stage was designed and simulated for output.

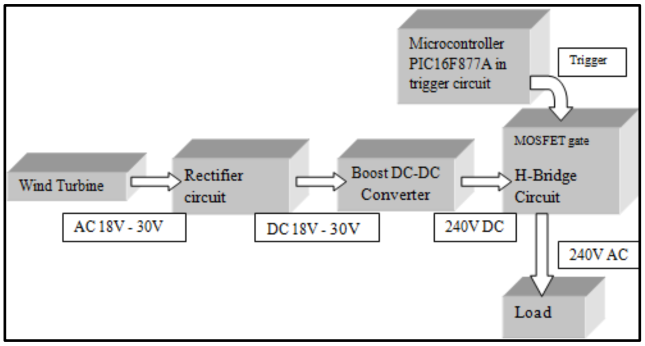

Figure 5 Block diagram of the experimental flow

C. *Design of a wind generator simulation rig*

Wind generator simulator rig was developed to test the performance of the power converter in case the wind speed of the identified sites did not reach the minimum steady speed of 3m/s since that was the startup speed of the wind generator [3].

In the rig design, the concept of wind generator simulation was to simulate the different wind speed by rotating the wind generator at different rotational speed. The relationship of wind speed and generator rotational speed for a specific wind turbine will be shown. The purpose was to observe generated power and response of power converter with respect of different wind speed. In the simulation, other factors such as effect of wind turbine blade and air density were neglected.

Aerodynamic power, Pt (W) captured by wind generator is dependent on the wind speed where the formula is given by:

$$P_t = \frac{1}{2} C_{P(\lambda)} \rho \pi R^2 v_w^3 \tag{1}$$

where ρ is air density (kg·m^{-3}), v_W is wind speed (m/s), C_P is coefficient of performance, and R is turbine blade radius (m). Tip speed ratio λ of a wind generator is ratio between the blade tip speed (m/s) to the wind speed (m/s).

$$\lambda = \frac{\text{Blade tip speed (m/s)}}{\text{Wind tip speed (m/s)}} \tag{2}$$

Blade tip speed can be calculated using the formula:

$$\text{Blade tip speed} = \frac{\text{Generator shaft rotational speed} \quad (\text{RPM})}{60\ (\text{s})} \times \pi \times 2R\ (\text{m}) \qquad (3)$$

From the formula (2) and (3), relationship between the wind speed (m/s) and generator rotational speed (rpm) for a specific wind turbine could be derived as follows:

$$v_G = \frac{30\lambda v_{\text{w}}}{\pi R} \qquad (4)$$

where v_G is generator shaft rotational speed (rpm), v_{w} is wind speed (m/s), λ is Tip Speed Ratio, and R is turbine blade radius (m).

From manufacturer performance data of 500W Wind Generator, radius of the turbine blade was 1.35m, rated shaft rotational speed was 600rpm at rated wind speed of 7m/s [3]. Tip Speed Ratio of this turbine was calculated using formula (2) and (3) where the value was 12.11. Hence, for this particular wind generator, formula of (4) can be further reduced:

$$v_G = 85.65 v_{\text{w}} \qquad (5)$$

To simulate wind speed to 5m/s based from formula (5), shaft of wind generator needs to be rotated at 428 rpm at least. Torque of an electric motor can DC motor was selected as prime mover to rotate the wind generator. This was due to ability to change the rotation speed of motor shaft by varying the DC supply voltage to the motor. The rotating generator part without the wind blade was taken from the wind generator set assembly. Connection of the DC motor to the wind generator was through a direct coupling. Hence, motor with adequate torque power was needed to rotate the wind generator at desired speed.

Below is the calculation of minimum torque needed to rotate wind generator:

Weight of wind generator, $m_1 = 6.5$ kg

Weight of transmission element, $m_2 = 0.5$ kg

Total mass weight, $m = m_1 + m_2 = 7.0$ kg

Perpendicular radius of transmission element, $R = 0.11$ m

$$\begin{aligned} \text{Torque} &= \text{perpendicular radius}, R \times m \times g \qquad (6) \\ &= (0.11\ \text{m}) \times (7.0\ \text{kg}) \times (9.81\ \text{m}/s^2) \\ &= 7.55\ \text{N·m} = 1069.17\ \text{oz·in} \end{aligned}$$

Required power for DC motor can be calculated through the formula below:

$$\text{Power} = \frac{\text{Required rotational speed} \quad (\text{RPM}) \times \text{Required torque} \quad (\text{oz·in})}{1350} \qquad (7)$$

$$= \frac{428 \times 1069.17}{1350} = 339\ \text{W}$$

But DC motor with rating more than 300W was very difficult to find in local market and also is very costly. Hence, DC motor with rating 300W was used with slightly compromising maximum wind speed it can emulate. From (7), motor with 300W can rotate wind generator rig at 10% less than intentional speed.

Figure 6 shows the experimental rig for the wind generator simulator. In this rig, wind generator was connected to a geared DC motor through a flexible coupling. The output of the rig was connected to a resistive load. It has been indicated by Vendor of this 500W Wind Turbine that rated Wind Generator output for this model is 500W at wind speed of 7m/s, where the rotational speed was at 600 rpm, while the start-up speed for the Wind Generator to operate was at wind speed of 3m/s. Variable Output Power Supply was used to generate various input supply voltage to DC motor, which in turn rotated wind generator at different speed between 118 rpm to 400 rpm.

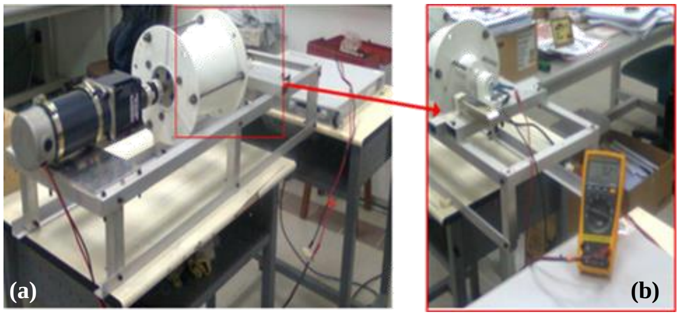

Figure 6 (a) Experimental rig for wind generator simulator; (b) Turbine rotational speed and generator terminal output measurement

Inverter circuit main job function is to invert the stepped up voltage of 240V from DC to AC. The output voltage must be ideal sine wave with frequency at 50Hz and low total harmonic distortion. The circuit consists of H-bridge circuit and control trigger circuit.

D. *Filtering of output voltage*

For an AC output voltage with low distortion, and the output frequency is constant, L-C low-pass filter circuit is used to decrease distortion. The voltage on the output of the filter will closely resemble the shape and frequency of the modulation signal. This means that the frequency, wave-shape, and amplitude of the inverter output voltage can all be controlled as long as the switching frequency is at least 25 to 100 times higher than the fundamental output frequency of the inverter.

The basic principle is simple. The filter circuit is a frequency-dependent voltage divider. Under ideal conditions, the transfer ratio (Vout/Vin) for the fundamental is equal to one, and for the other harmonics it is equal to zero. In the basic version of the filter circuit as in **Figure 7**, the ideal behavior is approximated using a series resonant circuit in the input of the filter, and a parallel resonant circuit in the output. The circuit is tuned to the fundamental frequency. Therefore, the transfer ratio for the fundamental is equal to one, and the inverter is not loaded with the reactive power of the parallel output capacitance. For the harmonics, the series impedance increases with frequency, and the parallel impedance decreases. This effect ensures a certain reduction in the harmonic voltages. If this reduction is not adequate, the series resonant circuits, which are tuned to various harmonic frequencies, will be connected in parallel with the output. The resulting output will be short-circuited at the chosen frequencies. The dynamic behavior of this filter circuit is not good at load jumps because of the large number of energy-storage elements. Since modern converter circuits are used with a high internal frequency (e.g., 20 kHz at PWM), the necessary filter circuit is simpler. If an output transformer is also used, the transformer values are calculated such that the series inductance of the filter circuit is given by the transformer's leakage inductance and the parallel inductance is equal to the transformer's magnetizing inductance. To ensure the required magnetizing inductance, the application of an air gap in the iron core is necessary. Using modern converter techniques, low distortion levels (a few percent) and very good dynamic behavior (5 to 10% overshoot at load jumps) can be achieved [15].

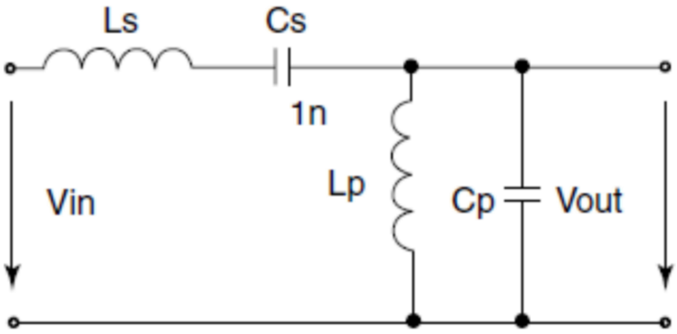

Figure 7 LC Filtering at Output [15]

E. *Programming microcontroller*

Microcontroller used in the system, particularly in the trigger circuit for Inverter Control is of model PIC16F877A. It is a 40-pin enhanced flash-type microcontroller produced by Microchip. This microcontroller was used to generate reference sine wave, carrier sawtooth wave, and also the two pulse control signals, which were out of phase from each other. Some of the key features of the microcontroller which were useful for the project, among others are 2 internal comparators, 5 Input/Output ports, 8 channel 10-bit analog to digital converter (Microchip, 2003).

After successful simulation of the control algorithm using MATLAB SIMULINK, hardware version of trigger control circuit is built and the algorithm was translated into C program that will be used by microcontroller. The trigger circuit mainly consisted of microcontroller PIC16F877A, comparator IC LM324, IC 74244. The microcontroller generates reference sine wave, carrier sawtooth wave, and also the two pulse control signals which were out of phase from each other. Through firmware, the reference sine wave signal was generated at Port B with frequency of 50Hz. Sawtooth carrier signal was generated at frequency 2kHz through initialization of PWM Module at pin CCP1 where the pulse signal was later modified to be sawtooth by filtering. Internal comparator modules C1 and C2 were activated through microcontroller firmware.

III. RESULTS AND ANALYSIS

A. *Results of wind generator simulator rig*

Test run results of the wind generator simulator rig based on design that has been described in II.C is shown in Figure 8. Wind generator was rotated by DC motor at various speed as the output was connected to a resistive load. The data for simulator rig starts at lower speed due to constraints of DC motor as prime mover to the rig. The result from the graph agrees with the manufacturer performance datasheet whereas the rotational speed increases due to increasing wind speed, the voltage output increase. From the graph, the generated voltage at wind speed ranging from 3m/s to 5m/s was around 13V to 20V.

The generated voltage at the terminal was single phase AC type with a variable frequency that also increases as the speed increase. From the simulation rig, power generated across the load was slightly above 40W. Hence rating for components at rectifier circuit was selected to be within 50V for voltage and 50W for power.

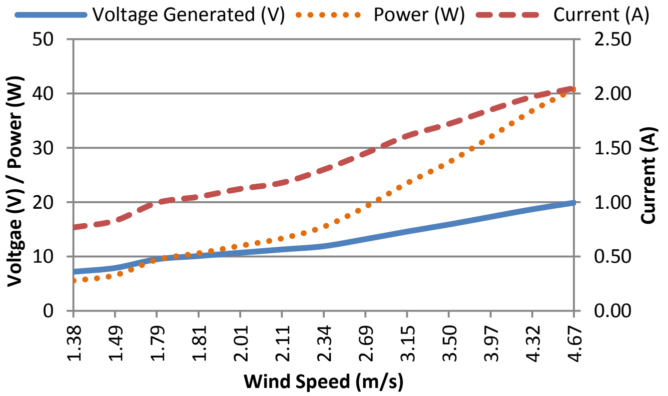

Figure 8 Wind Generator Simulator Rig output at different generator rotational speed

B. *Simulation results of inverter*

Simulation results of the inverter system are shown in **Figure 9**. The control algorithm for the generation of trigger control signal method using unipolar switching SPWM has been explained in II.B. Amplitude modulation ratio was selected to be at 0.8 because ratio of less than 1 has linear effect on amplitude of fundamental frequency component while ratio exceeding 1 will have noticeable increase in output distortion. Frequency modulation ratio was selected to be at 40 to be sufficiently high to enable better control of amplitude, wave shape and frequency of the inverter output. Reference sinusoidal frequency was selected at 50Hz while carrier sawtooth frequency was selected at 2 kHz. These parameters were also comparable with works by [6] that selected values to be 0.8 and 150 respectively.

Figure 9(a) shows output voltage after the MOSFET H-bridge circuit. The input to the H-bridge circuit was 240V DC voltage. The output was deployed as PWM pulses with amplitude 240V along the positive and negative sides. The output obtained is not sinusoidal because the LC filter was not included in the design. **Figure 9(b)** shows the output voltage after implementing the LC filtering components in the circuit.

From the graph the output voltage has sinusoidal shape with amplitude 240V and frequency 50Hz which has met criteria set by objective. THD measurement of the output voltage after LC filtering was 2.3% as shown in **Figure 9(c)**.

C. *Experiment results of inverter*

This section includes final experimental results obtained after running the Wind Simulator Rig with inverter system connected as per selected topology in Figure 6. The rig was run at 300 rpm (which is equivalent to wind speed of 3.5m/s) to generate around 20V of energy at terminal. A resistive load with resistance 480ohm and power rating 120W was connected at inverter output.

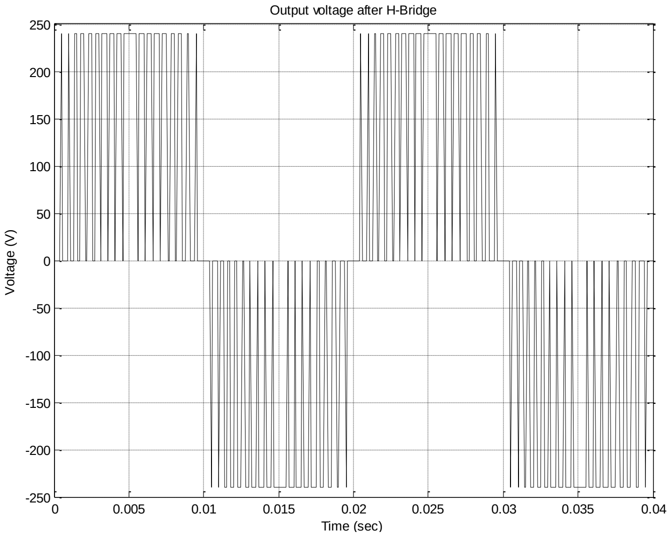

Figure 9(a) Output voltage after the H-bridge circuit before LC filtering

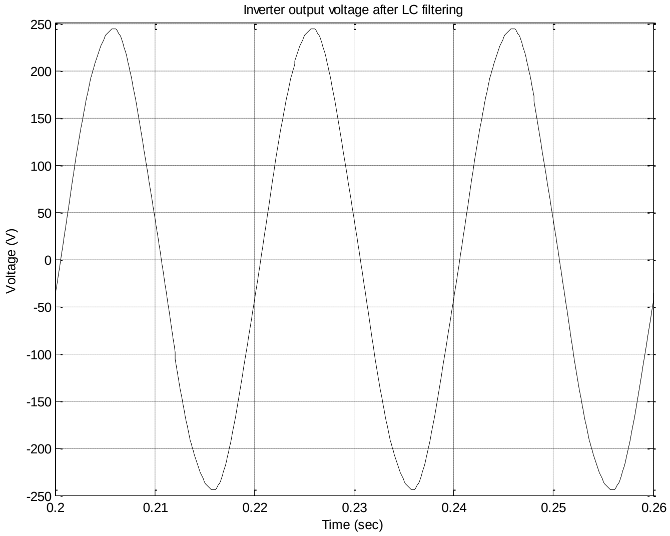

Figure 9(b) Output voltage after LC filtering

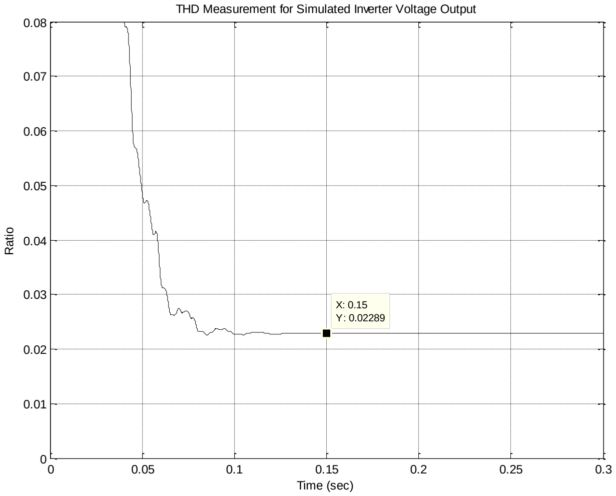

Figure 9(c) THD Measurement of simulated output voltage after LC filtering

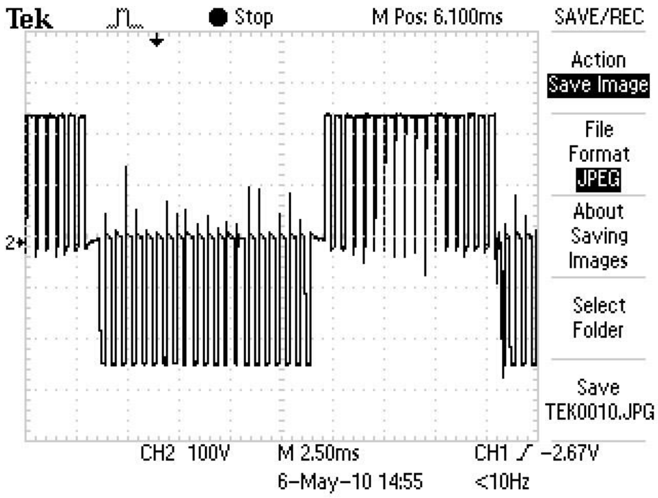

Figure 10(a) Output voltage after H-bridge circuit on prototype board

Figure 10(a) shows the output of the voltage after the MOSFET H-bridge circuit before LC filter. The output was deployed as PWM pulses with amplitude 240V along the positive and negative sides. Figure 10(b) shows the output voltage after implementing the LC filtering components in the circuit. From the graph, the output voltage has sinusoidal shape with amplitude 240V and frequency 50Hz which has met criteria set by objective. The sinusoidal output voltage signal was then sampled as data where the Fourier Transform was calculated for each sample points. Then the THD was calculated using formula from [1].

TABLE II shows summary of results for simulation and experimental. In the simulation, output voltage of inverter design using unipolar switching SPWM achieved all requirements set by the objectives. Experimental results of inverter output voltage where the inverter system is connected to the wind generator simulator rig rotated at 300rpm. Both simulation and experimental results showed that research design objectives have been achieved. By comparison with past works [6], in the simulation, both output voltage shown in **Figure 9(a)** matched the simulation result, while in the experiment, only output voltage before filtering in **Figure 10(a)** matched the experimental result. However, filtered output in **Figure 10(b)** has basic resemblance with experimental result.

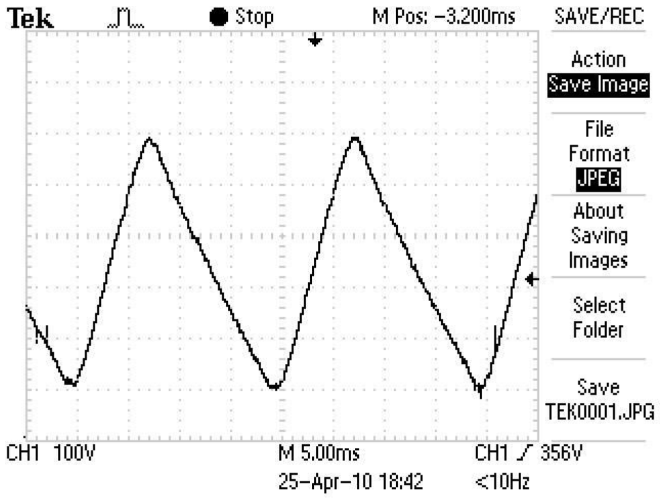

Figure 10(b) Inverter output voltage after LC filtering on prototype board

TABLE II SUMMARY OF RESULTS FOR INVERTER CIRCUIT OUTPUT

Parameters	**Simulated unipolar spwm**	**Experiment unipolar spwm**	**Objective**
Peak amplitude	240V	240V	216V – 252V
Frequency	50Hz	50Hz	50Hz
THD	2.3%	4.0%	less than 5%

IV. CONCLUSIONS

In this paper, simulation and experimental results were included together with explanation and analysis. Final simulation result complied with the project objective that the output of inverter voltage should be sinusoidal with peak voltage 240V, frequency 50Hz and THD below 5%. Finally when the rig was run with all hardware connected according to topology, the measured output voltage complies with the project objective, which voltage should be sinusoidal AC with peak voltage 240V, frequency 50Hz and THD below 5%.

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